PHYSICAL AND CHEMICAL HYDROLOGY OF GREAT SALT LAKE, UTAH

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Abstract.—Since 1851 the stage of Great Salt Lake has ranged from a high of 4,211.6 feet above mean sea level (in 1873) to a low of 4,191.35 feet (in 1963). In 1873 and 1963 the dissolved-solids concentrations of the brine were about 15 and 28 percent, respectively, but the composition of the dissolved solids remained virtually constant. About 2 million tons of dissolved solids (chiefly sodium and chloride) and 1 million acre-feet of water annually were contributed to the lake by surface sources during the 1960 and 1961 water years. In 1873 the lake contained about 6 billion tons of solids in about 30 million acre-feet of water, and in 1963 about 4 billion tons in about 9 million acre-feet. Two parts of the lake separated by a causeway built in 1957 are affected differently by inflow and evaporation. The resulting differences in density and head cause two-directional flow, near the surface and at depth, respectively, through culverts in the causeway and probably through the fill itself.

Levels of closed lakes change continuously in response to climatic changes and tend to maintain equilibrium between inflow to the lakes and evaporation from their surfaces. The chemical characteristics of lake water change with changes in stage and volume. A general downward trend in the level of Great Salt Lake since the early 1870's has long been of concern and has caused speculation regarding possible desiccation of the lake. Changes in the lake's chemical composition, which affect the commercial extraction of minerals from the brine and the recreational uses of the lake, have been of more recent concern. In recent years the U.S. Geological Survey has studied the chemical hydrology of Great Salt Lake and its surficial inflow in cooperation with the University of Utah and the Utah Geological and Mineralogical Survey. Recent studies, which have shown the hydrology of Great Salt Lake to be very complex, are being continued to gather information systematically on the physical and chemical characteristics of the lake. This article reviews changes in stage and salinity of the lake since records began in 1851, describes the results of a mineral-inflow study made during the water years 1960–61, discusses the chemical character of the lake brine, and presents some results of the current study of mineral transport within the lake.

Great Salt Lake, in northern Utah and the northeastern part of the Great Basin, is the largest surface-water body in the Western Hemisphere which does not drain to the ocean. It is the remnant of Lake Bonneville, a Pleistocene lake which, while not directly associated with continental glaciation, was formed as a result of the same climate which caused extensive glaciation. Lake Bonneville had an area of about 20,000 square miles at its highest level during late Pleistocene time; it reached a depth of 1,000 feet before overflowing the rim of the basin at Red Rock Pass, about 20 miles northwest of Preston, Idaho, and discharging to the ocean through the Portneuf, Snake, and Columbia Rivers. With the return of warm and dry climate, evaporation from the lake surface exceeded inflow and the lake receded.

CHANGES IN WATER LEVEL

When the pioneers reached Great Salt Lake in 1847 its water-surface elevation was about 4,200 feet above mean sea level (fig. 1) and its maximum depth was about 35 feet. During a series of wet years from 1862 to 1868 the stage of the lake rose almost 12 feet; precipitation for that 7-year period provided a greater water supply to the Great Basin than for any similar period during the past several hundred years. Evidence from shorelines and vegetation (Gilbert, 1890, p. 242–243) shows that for some centuries the level of the lake had been lower than that recorded in 1865. The maximum recorded elevation of the lake was 4,211.6 feet in 1873, but during a series of dry years from 1873 to 1904 the stage receded almost 16 feet. Since 1904 the lake level has fluctuated between about

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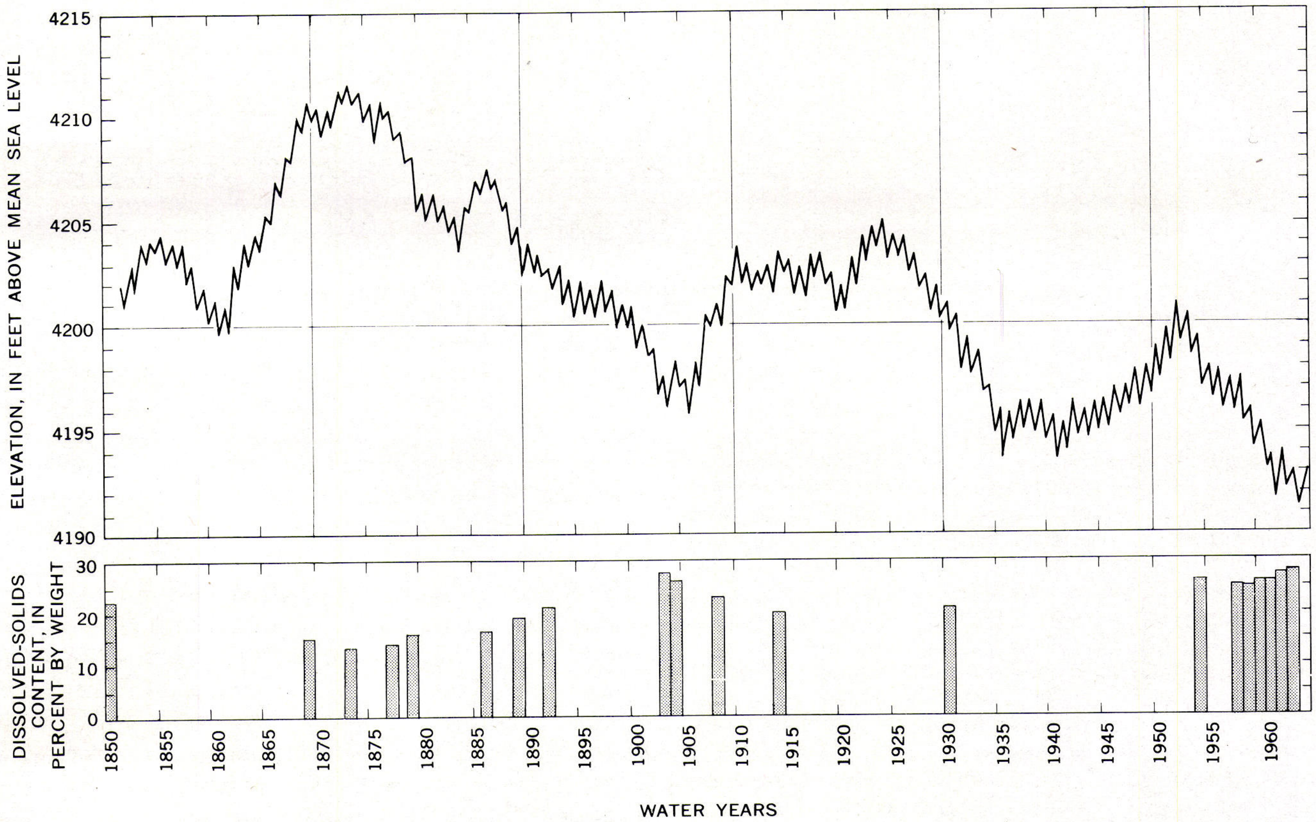

FIGURE 1.—Hydrograph of Great Salt Lake (above), showing yearly maximum and minimum lake-surface elevations, 1851–1963; and bar graph showing the dissolved-solids content of the brine (below).

4,191 and 4,205 feet; the greatest decrease in stage (11 feet) was during the drought period of the late 1920's and early 1930's. The lowest stage recorded was 4,191.35 feet, on November 1, 1963.

Large changes in streamflow are soon reflected by changes in lake stage. During 1907 the lake stage increased 3 feet, and during 1909, 2 feet. During the drought years of 1931, 1934, and 1961 the stage of the lake dropped about 2 feet each year. Although the stage is affected by increased consumptive use of water in the basin, the general downward trend since 1873 does not necessarily mean that the lake will dry up in the near future. The lake tends to maintain a balance between the amount of water evaporated from its surface and the amount of water contributed to it by surface streams, by ground-water inflow, and by precipitation on its surface. During a period of dry years the stage falls, the surface area decreases rapidly, and the mineralization increases. All these changes favor decrease in the total volume of evaporation, and less inflow is required to maintain the lower lake stage. Conversely, during a period of wet years the stage rises, the surface area increases appreciably, and mineralization decreases; thus, a larger volume of evaporation compensates for the greater inflow. Over a period of years the lake's surface elevation therefore tends to stabilize. At the high stage in 1873 the area of the lake's surface was about 2,400 square miles; at the low stage in 1963 it was about 940 square miles.

DISSOLVED-MINERAL INFLOW

Preliminary findings of Diaz (1963) show that the Bear River and the drains which discharge municipal and industrial waste water contributed more than half of the 2 million tons of dissolved solids that entered Great Salt Lake in 1960 from surface sources; the Jordan River and the springs which discharge near the lakeshore contributed about one-third. These findings were substantiated in a later report (Hahl and Langford, 1964) in which similar data were presented for the 1961 water year. Although the dissolved-solids inflow was less during 1961 (1.7 million tons), the relative amounts contributed by the several sources remained the same as in 1960. Ground-water inflow during 1960 and 1961 was estimated to be half a million acre-feet annually, and the dissolved-solids load contributed by ground water was estimated to be half a million tons annually.

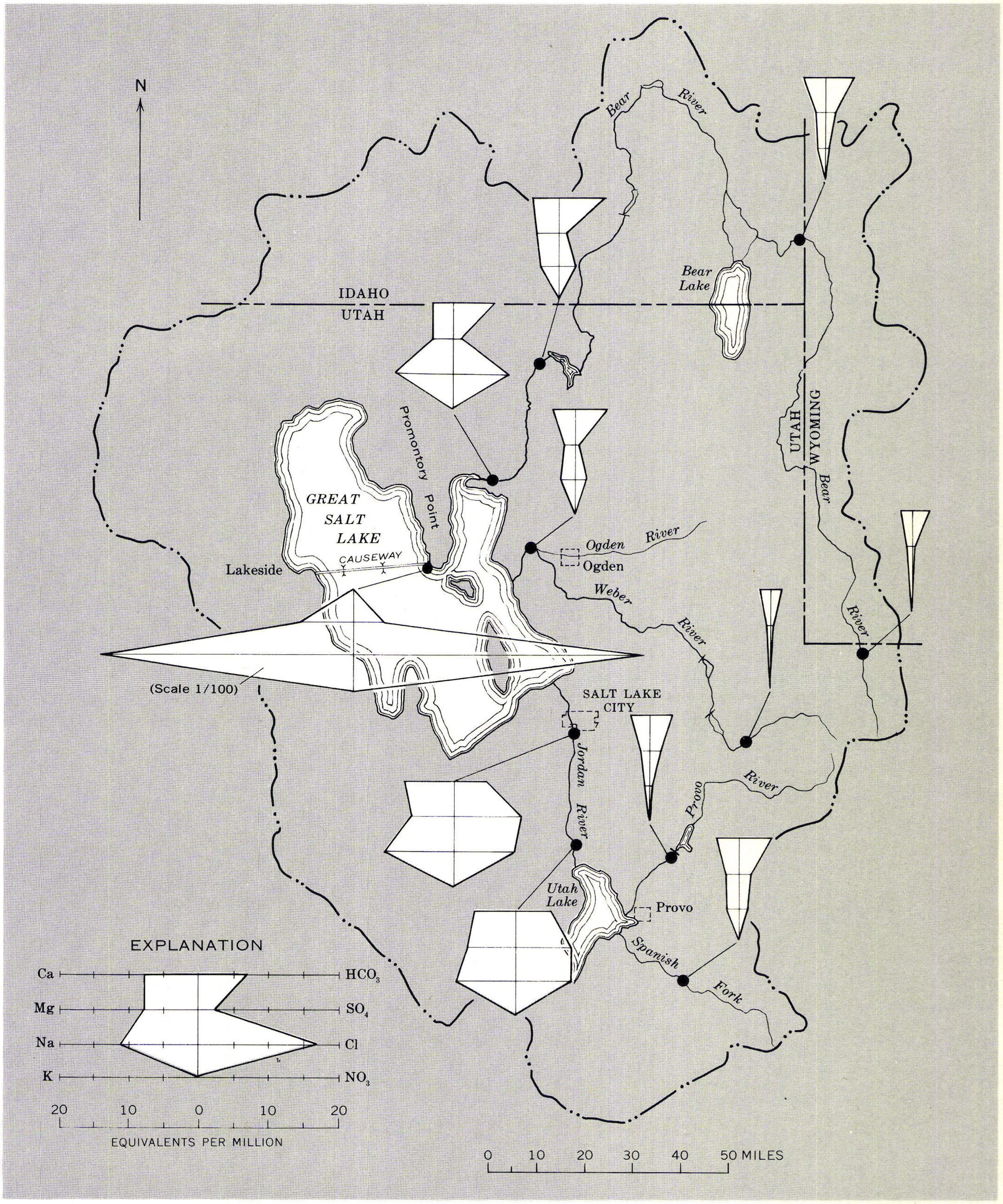

FIGURE 2.—Chemical quality of water at selected sampling sites in the Great Salt Lake basin (enclosed by dashed and dotted line). Sampling sites are shown by large dots, and the dissolved-solids content of the water is indicated by chemical diagrams. The horizontal scale of the chemical diagram for Great Salt Lake is only 1/100 of that of the other diagrams.

About 82 percent of the surface inflow of water to the lake during the water years 1960–61 came from the Bear, Jordan, and Weber Rivers; however, only about 55 percent of the dissolved-mineral load was contributed by these three rivers. The remainder of the mineral load was contributed chiefly by springs, drains, and sewage canals (Hahl and Langford, 1964).

The most abundant dissolved mineral constituents entering the lake during the 2-year period were sodium and chloride. Figure 2 shows the chemical characteristics of surface inflow to the lake from its major tributaries. The constituents of the dissolved solids in the surface inflow during the 1960 and 1961 water years are shown in table 1.

TABLE 1.—*Constituents of the dissolved solids, in percent by weight*

Silica, SiO_2	1.3
Calcium, Ca^{+2}	7.1
Magnesium, Mg^{+2}	3.7
Sodium, Na^{+1}	22.7
Potassium, K^{+1}	1.5
Bicarbonate as carbonate, CO_3^{-2}	12.8
Sulfate, SO_4^{-2}	14.3
Chloride, Cl^{-1}	36.3
Nitrate, NO_3^{-1}	.3
Total	100.0

Downstream changes in water quality, depicted diagrammatically on figure 2, result from changes in environment. For example, most runoff in the three major streams entering Great Salt Lake originates as snowmelt or rainfall in the Uinta Mountains and Wasatch Range, in the eastern part of the drainage basin. This runoff is of the bicarbonate type and is generally of excellent chemical quality. In the lower reaches of these rivers, evapotranspiration, return flows from irrigated lands, discharge of industrial and municipal wastes, and ground-water inflow cause the water quality to change; sodium, chloride, and sulfate become major dissolved constituents.

CHEMICAL CHARACTER OF THE BRINE

The concentration of dissolved solids (in percent by weight) in the lake brine has ranged from about 15 percent during the high lake stages of the 1870's to about 28 percent during the low lake stages of the early 1900's and 1960's (fig. 1). The relation between lake stage or lake volume and dissolved-solids concentration is nearly linear between stages of about 4,195 and 4,205 feet. A preliminary review of historical data indicates that the dissolved-solids concentration of the brine appears to approach a maximum of 28 to 29 percent when lake volume is less than about 10 million acre-feet, and a minimum of 13 to 14 percent when volume is 25 to 30 million acre-feet.

Although the dissolved-solids concentration of the brine changes with time, the percentage composition of the dissolved solids has remained constant over the past hundred years. Sodium and chloride are the predominant constituents; sulfate, magnesium, and potassium are present in lesser amounts; and calcium, bicarbonate, and other substances are minor constituents. Extremes observed during 1959–61, average concentrations of individual constituents dissolved in the brine of the southern arm of the lake, and discharge-weighted average concentrations of surface inflow are given in table 2.

TABLE 2.—*Concentrations of dissolved constituents in Great Salt Lake brine and surface inflow, 1959–61*

[Concentrations in parts per million unless otherwise indicated]

Constituent or property	Great Salt Lake			Surface inflow (discharge-weighted average) [3]
	Maximum [1]	Minimum [1]	Average [2]	
Silica (SiO_2)	7.0	4.2	5.3	18
Aluminum (Al)	2.6	2.5		
Iron (Fe)	.11	.02	.04	
Calcium (Ca)	463	265	319	94
Magnesium (Mg)	9,440	6,920	8,050	49
Sodium (Na)	92,200	77,800	85,700	300
Potassium (K)	5,570	3,810	4,550	20
Lithium (Li)	56	29		
Bicarbonate (HCO_3)	398	266	327	344
Sulfate (SO_4)	22,600	12,100	17,400	188
Chloride (Cl)	158,000	133,000	147,000	475
Fluoride (F)	7.4	5.9		
Iodide (I)	.60	.26	.41	
Nitrate (NO_3)	154	61	82	4.1
Boron (B)	36	21		
Dissolved solids, calculated	285,000	240,000	263,000	1,320
Density, g/ml at 20°C	1.221	1.186	1.208	1.000

[1] Observed extremes (from analyses of samples collected in southern arm of lake during June 1959–November 1961).
[2] Average of analyses of samples collected in southern arm of lake in April, July, and October 1960, and January–February 1961.
[3] For water years 1960 and 1961.

The amount of mineral matter dissolved in the brine also fluctuates with lake volume. In 1873, when the lake was at its highest recorded stage, the lake volume was about 30 million acre-feet and the brine contained about 6 billion tons of dissolved solids. In contrast, at the low stage of November 1963, the volume was about 8.7 million acre-feet and the brine contained about 4 billion tons of dissolved solids.

Because the dissolved-solids concentration of the brine is about 200 times that of the surface inflow (table 2), it is virtually unaffected by the minerals being delivered to the lake each year. The effect of inflow is to change the volume of the lake and, thus, to act as a diluent. With increasing volume the dissolved-solids concentration of the brine decreases, but the total amount of mineral matter dissolved in the brine increases. This increase in total dissolved solids seems to result mainly from re-solution of salts that had been precipitated on the lakebed and shore or otherwise left behind as the volume was decreasing. Therefore, the chemical characteristics of the brine are controlled mainly by the minerals dissolved in the brine and by the salts on the lakebed which are available for solution. Physiographic features of the lakebed, and aquatic life in the brine, may also affect the dissolved-solids concentration and chemical character of the brine.

EFFECT OF A CAUSEWAY ON CONCENTRATION

In the late 1950's a causeway was constructed across the lake between Promontory Point and Lakeside. As a result, one-third of Great Salt Lake is now separated from the main body of brine by a permeable fill of quarry-run rock. Two culverts, each 15 feet wide, allow free flow of brine through the fill to a depth of about 10 feet (the lake here is about 25 feet deep). The southern arm of the lake is fed mainly by relatively fresh water from the major tributaries (Bear, Weber, and Jordan Rivers), but the northern arm has been fed (since 1957) mainly by brine which flows northward through the fill and culverts. Therefore, the dissolved-solids concentration in the northern arm probably will fluctuate less, and the brine will become more concentrated there, than in the southern arm. The amount of seasonal change in concentration in the southern part of the lake is determined largely by the amount of inflow from the major tributaries. During years of low runoff, the lake volume decreases and the brine approaches saturation; during years of high runoff the volume increases and the brine becomes less concentrated.

Because about 95 percent of the total surface inflow (about 2 million acre-feet per year as a long-term average) enters the southern arm of the lake, the water level there is higher during the season of greatest inflow than in the northern arm, and brine movement should be from the southern to the northern arm. Inflow is greatest during the spring and is relatively small during the summer months when evaporation is the greatest. When evaporation equals inflow, usually during the months of July and November, the levels of the lake on each side of the causeway approach equilibrium. Flow through the fill during these periods should be small except when other influences such as wind increase the level on one side and decrease it on the other. On several occasions after periods of calm weather, however, flow from the northern to the southern arm of the lake was observed. Velocity profiles in the culverts, measured twice within 3 weeks during the fall of 1963, showed that the upper 4 feet of water in the culverts flowed northward while the lower 5 feet flowed southward. On November 14, 1963, the difference in head between the mean lake surface on the southern and northern sides of the fill was about three-fourths of an inch. The brine flowing northward had a density about 2 percent less than that of the brine flowing southward. On the basis of these observations we conclude that density differences coupled with small head differences probably can cause opposing flows to occur simultaneously through the fill as well as through the causeway openings.

Older observations, of which there are relatively few, suggest that there are no great differences in concentration from point to point in the lake or from one part of a vertical section to another. Recent data indicate, however, that inflowing tributary waters and precipitation falling on the lake tend to form a layer at the lake surface which persists for some time before the fresher water mixes with the brine beneath. Such a layer, observed in the lake about 12 miles from the mouth of Bear River, south of the causeway, and west of Promontory Point, seemed to persist for several weeks in spite of a moderate windstorm during that period.

These discoveries of simultaneous two-directional flow between the two arms of the lake, and of the presence of a layer of dilute water on the surface of the brine, which show the chemical and physical environment in Great Salt Lake to be more complex than was formerly realized, should be helpful in studies of evaporation from the brine and of mineral transport in the lake.

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